# Cambridge

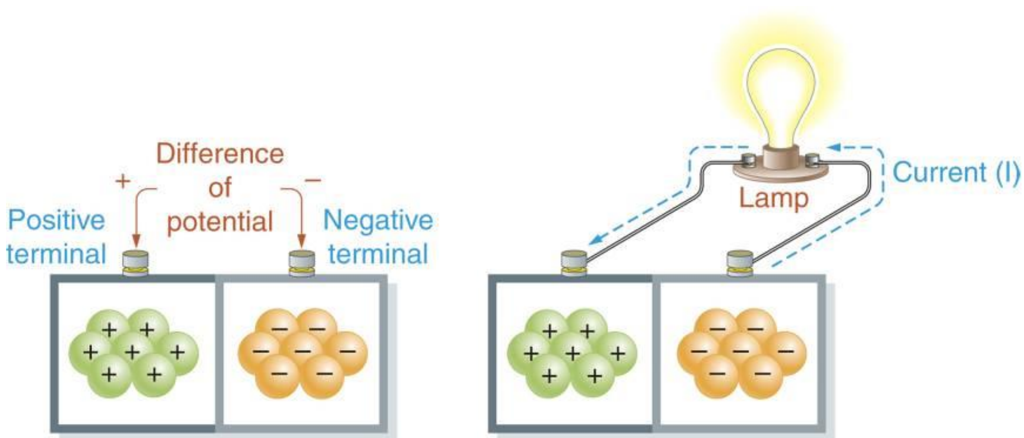
# IGCSE

# Physics

CODE: (9702)

# Chapter 09

# Electric current, potential difference and resistance



# Circuit symbols and diagrams

Circuit diagrams are essential for drawing complex circuits using standard symbols. These symbols are part of internationally agreed conventions for electrical components. Scientists, engineers, and manufacturers worldwide use the same symbol for each component. Many circuits are designed by computers, requiring a universal language for working and presenting results.

## What is in a word?

**Electricity** is a rather tricky word. In everyday life, its meaning may be rather vague – sometimes we use it to mean electric current; at other times, it may mean electrical energy or electrical power.

**Figure 9.4** A selection of electrical components, including resistors, fuses, capacitors and microchips.

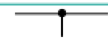
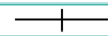
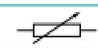
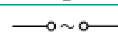
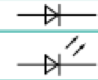
| Symbol | Component name |
|---|---|
|  | connecting lead |
|  | cell |
|  | battery of cells |
|  | fixed resistor |
|  | power supply |
|  | junction of conductors |
|  | crossing conductors (no connection) |
|  | filament lamp |
|  | voltmeter |
|  | ammeter |
|  | switch |
|  | variable resistor |
|  | microphone |
|  | loudspeaker |
|  | fuse |
|  | earth |
|  | alternating signal |
|  | capacitor |
|  | thermistor |
|  | light-dependent resistor (LDR) |
|  | semiconductor diode |
|  | light-emitting diode (LED) |

**Table 9.1** Electrical components and their circuit symbols.

## Electric current

**Electric current,** a scientific convention, is a fundamental element in everyday life, such as connecting a wire to a cell. Its direction is from the positive terminal of the cell to the negative terminal, making it known as **conventional current**.

A wire is made of metal. Inside a metal, there are negatively charged electrons which are free to move about. We call these **conduction** or **free** electrons, because they are the particles which allow a metal to conduct an electric current.

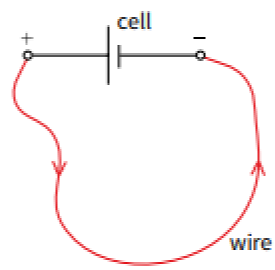



**Figure 9.5** There is current in the wire when it is connected to a cell.

When a cell is connected to a wire, it exerts an electric force on conduction electrons, causing them to travel along the wire's length. Negatively charged electrons flow away from the negative terminal and towards the positive terminal, opposite to conventional current. This is because the direction of conventional current was chosen before anyone knew what was happening inside a metal carrying a current. The current exists at all points in the circuit, as charged electrons are already present before the cell is connected.

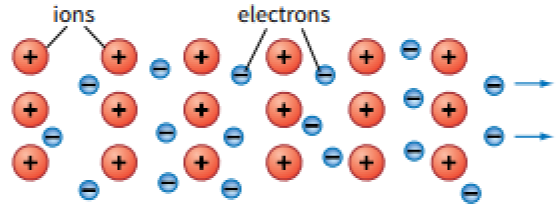



**Figure 9.6** In a metal, conduction electrons are free to move among the fixed positive ions. A cell connected across the ends of the metal causes the electrons to drift towards its positive terminal.

### Charge carries

A current is a flow of positive or negative charges, such as protons in particle accelerators, or both. **Charge carriers**, such as electrons, protons, or ions, contribute to an electric current by moving in opposite directions in a conductor-connected solution.

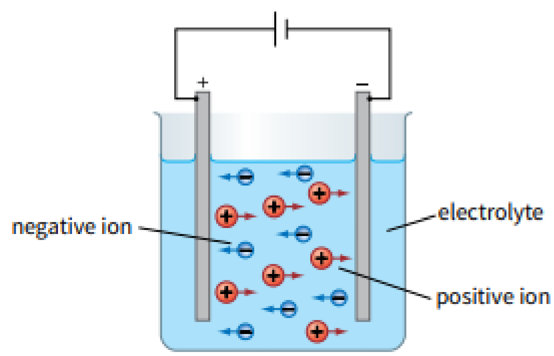



**Figure 9.7** Both positive and negative charges are free to move in a solution. Both contribute to the electric current.

### Current and charge

When charged particles flow past a point in a circuit, we say that there is a current in the circuit. Electrical current is measured in **amperes** (A).

The relationship between charge, current and time may be written as the following word equation

$$\text{current} = \frac{\text{charge}}{\text{time}}$$

This equation explains what we mean by current.

Electric current is the rate of flow of electric charge past a point.

The equation for current can be rearranged to give an equation for charge:

$$\text{charge} = \text{current} \times \text{time}$$

This gives us the definition of the unit of charge, the coulomb.

One coulomb is the charge which flows past a point in a circuit in a time of 1 s when the current is 1 A.

In symbols, the charge flowing past a point is given by the relationship:

$$\Delta Q = I\Delta t$$

where $\Delta Q$ is the charge which flows during a time $\Delta t$ and $I$ is the current.

### Charged particles

As we have seen, current is the flow of charged particles called charge carriers. But how much charge does each particle carry?

Electrons each carry a tiny negative charge of approximately $-1.6 \times 10^{-19}$ C. This charge is represented by $-e$. The magnitude of the charge is known as the elementary charge. This charge is so tiny that you would need about six million million million electrons – that's 6 000 000 000 000 000 000 of them – to have a charge equivalent to one coulomb.

elementary charge $e = 1.6 \times 10^{-19}$ C

Protons are positively charged, with a charge $+e$. This is equal and opposite to that of an electron. Ions carry charges that are multiples of $+e$ and $-e$.

## An equation for current

Copper, silver and gold are good conductors of electric current. There are large numbers of conduction electrons in a copper wire – as many conduction electrons as there are atoms. The number of conduction electrons per unit volume (e.g. in $1m^3$ of the metal) is called the **number**

density and has the symbol n. For copper, the value of n is about $10^{29}$ $m^{-3}$

Figure 9.9 shows a length of wire, with cross-sectional area A, along which there is a current I. How fast do the electrons have to travel? The following equation allows us to answer this question:

$$I = nAvq$$

Here, v is called the **mean drift velocity** of the electrons and q is the charge of each particle carrying the current.

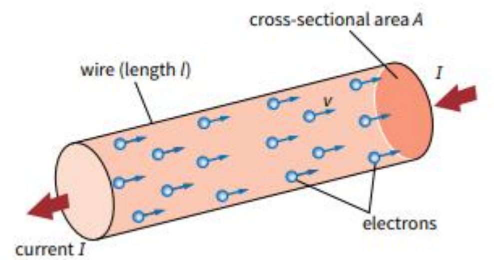


**Figure 9.9** A current $I$ in a wire of cross-sectional area $A$. The charge carriers are mobile conduction electrons with mean drift velocity $v$.

## Deriving $I = nAve$

In Figure 9.9, a wire with a length of l is used to determine the speed of electrons. The first electron emerges from the right-hand end and the last takes time t to travel the distance. The number of electrons and charge flow in time t are calculated.

$$\text{number of electrons} = \text{number density} \times \text{volume of wire}$$
$$= n \times A \times l$$

$$\text{charge of electrons} = \text{number} \times \text{electron charge}$$
$$= n \times A \times l \times e$$

We can find the current $I$ because we know that this is the charge that flows in time $t$, and current = charge/time:

$$I = n \times A \times l \times e / t$$

Substituting $v$ for $l / t$ gives

$$I = nAve$$

The moving *charge* carriers that make up a current are not always electrons. They might, for example, be ions (positive or negative) whose charge q is a multiple of e. Hence we can write a more general version of the equation as

$I = nAve$

## Slow flow

Electrons in a copper wire drift at a fraction of a millimetre per second due to their haphazard journey. When connected to a battery or external power supply, each electron experiences an electrical force, causing them to move towards the positive end of the battery. The mean drift velocity (v) of the electrons is used to explain this behavior.

The drift velocity of electrons can be visualized by comparing the flow of water in a river to the current in metals. Metals have a high electron number density, while semiconductors have lower values. Semiconductors have significantly higher mean drift velocities, while electrical insulators have few conduction electrons per unit volume.

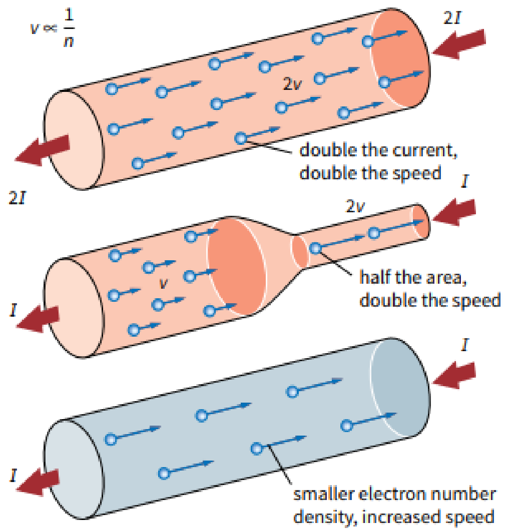



**Figure 9.10** The mean drift velocity of electrons depends on the current, the cross-sectional area and the electron density of the material.

Figure 9.10 shows how the mean drift velocity of electrons varies in different situations. We can understand this using the equation:

$$v = \frac{I}{nAe}$$

- If the current increases, the drift velocity $v$ must increase. That is:

  $v \propto I$
- If the wire is thinner, the electrons move more quicklyfor a given current. That is:

  $v \propto \frac{1}{A}$

  There are fewer electrons in a thinner piece of wire, so an individual electron must travel more quickly.
- In a material with a lower density of electrons (smaller $n$), the mean drift velocity must be greater for a given current. That is:

  $v \propto \frac{1}{n}$

## The meaning of voltage

The term "voltage" is often used casually, but it is crucial to understand its meaning in relation to electric circuits. In a simple circuit with negligible internal resistance, three voltmeters measure three potential differences. The voltage across the power supply is equal to the sum of the voltages across the resistors. Electric current is the rate of flow of electric charge.

Earlier in this chapter we saw that electric current is the rate of flow of electric charge. Figure 9.12 shows the same circuit as in Figure 9.11, but here we are looking at the movement of one coulomb (1C) of charge round the circuit. Electrical energy is transferred to the charge by the power supply.

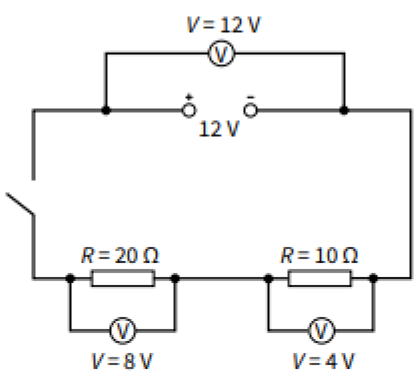



**Figure 9.11** Measuring voltages in a circuit. Note that each voltmeter is connected **across** the component.

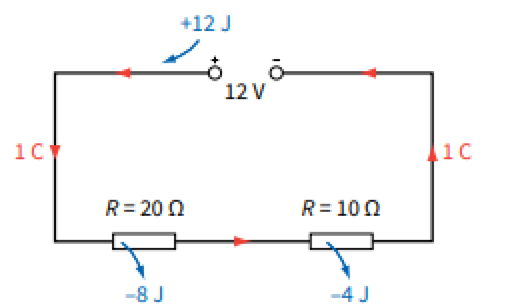



**Figure 9.12** Energy transfers as 1 C of charge flows round a circuit. This circuit is the same as that shown in Figure 9.11.

The **potential difference** (pd.) is the energy transferred per unit charge in a component, measured by voltmeters placed across resistors. It's important to be vigilant when interpreting terms like e.m.f. and potential difference, as they have different meanings.

A power supply or a battery transfers energy to electrical charges in a circuit. The e.m.f., E, of the supply is also defined as the energy transferred per unit charge

The potential difference between two points, A and B, is the energy per unit charge as charge moves from point A to point B.

e.m.f. is defined as the total work done per unit charge when charge flows round a complete circuit.

## Electrical resistance

If you connect a lamp to a battery, a current in the lamp causes it to glow. But what determines the size of the current? This depends on two factors:

■ The potential difference or voltage V across the lamp – the greater the potential difference, the greater the current for a given lamp

■The resistance R of the lamp – the greater the resistance, the smaller the current for a given potential difference

Now we need to think about the meaning of **electrical resistance.**

$$\text{resistance} = \frac{\text{potential difference}}{\text{current}}$$

or

$$R = \frac{V}{I}$$

where $R$ is the resistance of the component, $V$ is the potential difference across the component and $I$ is the current in the component. You can rearrange the equation above to give:

$$I = \frac{V}{R} \quad \text{or} \quad V = IR$$

Table 9.2 summarises these quantities and their units.

| Quantity | Symbol for quantity | Unit | Symbol for unit |
|---|---|---|---|
| current | $I$ | ampere (amp) | A |
| voltage (p.d., e.m.f.) | $V$ | volt | V |
| resistance | $R$ | ohm | Ω |

**Table 9.2** Basic electrical quantities, their symbols and SI units. Take care to understand the difference between $V$ (in italics) meaning the quantity voltage and V meaning the unit volt.

## Defining the ohm

The unit of resistance, the ohm, can be determined from the equation that defines resistance:

$$\text{resistance} = \frac{\text{potential difference}}{\text{current}}$$

The ohm is equivalent to '1 volt per ampere'. That is:

$$1\,\Omega = 1\,\text{V}\,\text{A}^{-1}$$

The ohm is the resistance of a component when a potential difference of 1 volt drives a current of 1 ampere through it.

## Electrical power

The rate at which energy is transferred is known as power. Power P is measured in watts (W).

$$\text{power} = \frac{\text{energy transferred}}{\text{time taken}}$$

$$P = \frac{W}{\Delta t}$$

The rate at which energy is transferred in an electrical component is related to two quantities:

■The current I in the component

■The potential difference V across the component.

The amount of energy W transferred by a charge ΔQ when it moves through a potential difference V is given by:

$$W = V\Delta Q$$

Hence:

$$P = \frac{W}{\Delta t} = \frac{V\Delta Q}{\Delta t} = V\left(\frac{\Delta Q}{\Delta t}\right)$$

The ratio of charge to time, $\frac{\Delta Q}{\Delta t}$, is the current $I$ in the component. Therefore:

P = VI As a word equation, we have:

power = potential difference × current and in units:

watts = amps × volts

## Fuses

A fuse is a device in an electric circuit designed to protect wiring from excessive currents, such as high currents in a domestic fuse box. Fuses are marked with their current rating, and a thin wire inside the cartridge melts if the current exceeds this limit.


**Figure 9.15** Fuses of different current ratings.

## Power and resistance

A current I transfers energy to a resistor, which dissipates it as heat, with the p.d. V = IR and P = VI equations providing further power dissipation.

$$P = I^2R$$

$$P = \frac{V^2}{R}$$

The equation's form depends on available information, as shown in Worked examples 6a and 6b, relating to a power station and its grid cables.

**Figure 9.16** A power station and electrical transmission lines. How much electrical power is lost as heat in these cables? (See Worked examples 6a and 6b.)

## Calculating energy

We can use the relationship for power as energy transferred per unit time and the equation for electrical power to find the energy transferred in a circuit. Since:

$$\text{power} = \text{current} \times \text{voltage}$$

and:

$$\text{energy} = \text{power} \times \text{time}$$

we have:

$$\text{energy transferred} = \text{current} \times \text{voltage} \times \text{time}$$

$$W = IV\Delta t$$

Working in SI units, this gives energy transferred in joules.

# Revision questions

1) The ends of a metal resistance wire are connected to a battery of electromotive force (e.m.f.) 8.0V and negligible internal resistance, as shown in Fig. 6.1.

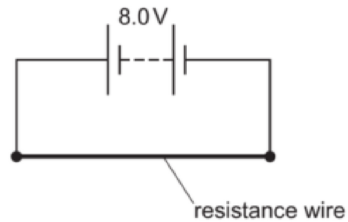



Fig. 6.1

(ii) the number of free electrons that pass through the resistance wire in a time of 50s

(iii) the resistance of the wire.

(b) The metal of the resistance wire in the circuit has a resistivity of 1.4 x 10 $^{-6}$ Ωm The cross-sectional area of the wire is 0.25 mm$^2$

(c) The circuit shown in Fig. 6.1 is modified by replacing the original resistance wire with a second resistance wire. The second wire has a greater diameter than the original wire. There are no other differences between the second wire and the original wire. By reference to resistance, state and explain whether the power dissipated by the second wire is more than, less than or the same as the power dissipated by the original wire.

(d) The circuit shown in Fig. 6.1 is modified by connecting a second battery, of e.m.f. 8.0V and negligible internal resistance, in parallel with the original battery and the original resistance wire, as shown in Fig. 6.2.

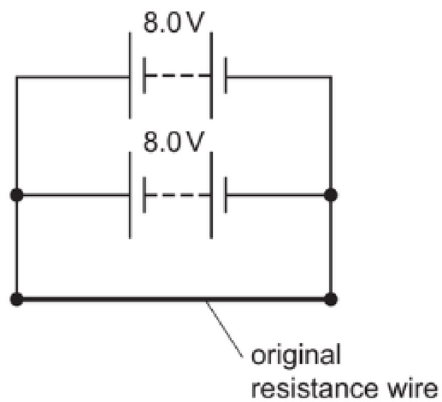



Fig. 6.2

By reference to the current in the resistance wire, state and explain whether the addition of the second battery causes the power in the original resistance wire to decrease, increase or stay the same

(b) A battery has electromotive force (e.m.f.) 4.0V and internal resistance 0.35Ω. The battery is connected to a uniform resistance wire XY and a fixed resistor of resistance R, as shown in Fig. 5.1.

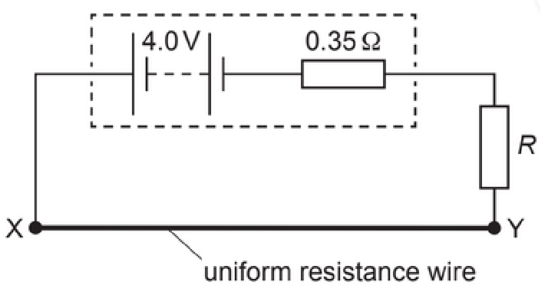



Fig. 5.1

Wire XY has resistance 0.90Ω. The potential difference across wire XY is 1.8V.

Calculate:

(i) the current in wire XY

current = ...................................................... A [1]

ii)the number of free electrons that pass a point in the battery in a time of 45s
(iii) resistance R.
(c) A cell of e.m.f. 1.2V is connected to the circuit in (b), as shown in Fig. 5.2.

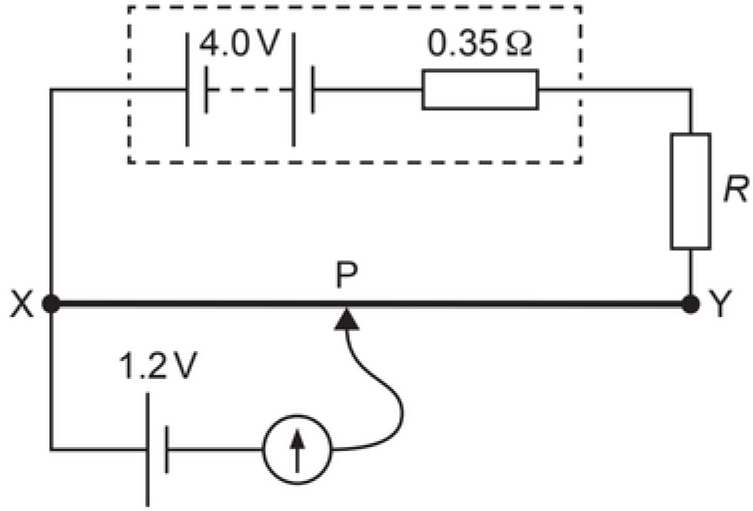



**Fig. 5.2**

The connection P is moved along the wire XY. The galvanometer reading is zero when distance XP is 0.30m.
(i) Calculate the total length L of wire XY.

(ii) The fixed resistor is replaced by a different fixed resistor of resistance greater than R. State and explain the change, if any, that must be made to the position of P on wire XY so that the galvanometer reading is zero.

3) The circuit shown in Fig. 5.1 contains a battery of electromotive force (e.m.f.) E and negligible internal resistance connected to four resistors $R_1$, $R_2$, $R_3$ and $R_4$, each of resistance R.
The current in $R_3$ is 0.30A and the potential difference (p.d.) across $R_4$ is 2.4V.

(i) Show that R is equal to 4.0Ω.

(ii) Determine the e.m.f. E of the battery.

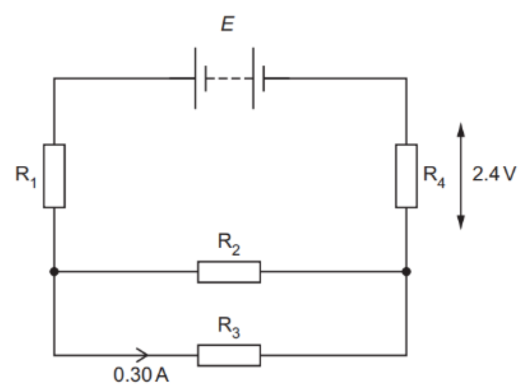



**Fig. 5.1**

(c) The battery in (b) is replaced with another battery of the same e.m.f. E but with an internal resistance that is not negligible.
State and explain the change, if any, in the total power produced by the battery.

(d) The resistors in the circuit of Fig. 5.1 are made from nichrome wire of uniform radius 240μm.
The length of this wire needed to make each resistor is 0.67m.
Calculate the resistivity of nichrome

4) (a) Define the ohm

b) A wire has a resistance of 1.8Ω. The wire has a uniform cross-sectional area of 0.38mm2 and is made of metal of resistivity 9.6 × $^{10-7}$ Ωm

Calculate the length of the wire.

b) A wire has a resistance of 1.8Ω. The wire has a uniform cross-sectional area of 0.38mm2 and is made of metal of resistivity 9.6 × 10–7Ωm.

Calculate the length of the wire.

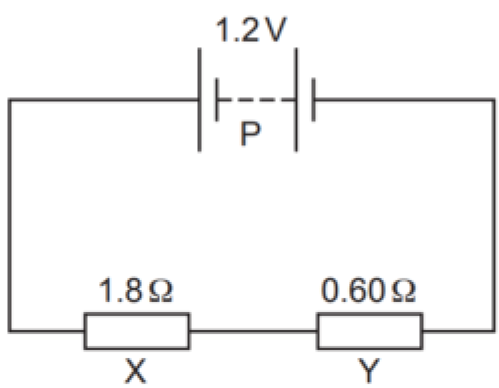



**Fig. 5.1**

The battery P has an electromotive force (e.m.f.) of 1.2V and negligible internal resistance.

(i) Explain, in terms of energy, why the potential difference (p.d.) across resistor X is less than the e.m.f. of the battery.

(ii) Calculate the potential difference across resistor X.

(d) Another battery Q of e.m.f. 1.2V and negligible internal resistance is now connected into the circuit of Fig. 5.1 to produce the new circuit shown in Fig. 5.2.

State whether the addition of battery Q causes the current to decrease, increase or remain the same in:

(i) resistor X

(ii) battery P.

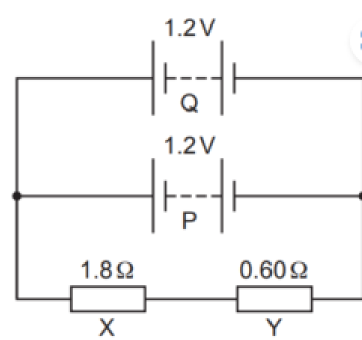



**Fig. 5.2**

5) The ends of a metal resistance wire are connected to a battery of electromotive force (e.m.f.) 8.0V and negligible internal resistance, as shown in Fig. 6.1.

The power dissipated by the resistance wire is 36W.

(a) Calculate:

(i) the current in the resistance wire

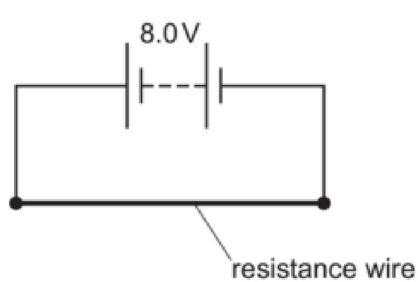



**Fig. 6.1**

(ii) the number of free electrons that pass through the resistance wire in a time of 50s

number = ........................................................ [2]

(iii) the resistance of the wire.

resistance = ..................................................... Ω [2]

(b) The metal of the resistance wire in the circuit has a resistivity of $1.4 \times 10^{-6}$ Ω-m. The cross-sectional area of the wire is 0.25 $mm^2$.
Determine the length of the wire.

length = .....................................................m [2]

(c) The circuit shown in Fig. 6.1 is modified by replacing the original resistance wire with a second resistance wire. The second wire has a greater diameter than the original wire. There are no other differences between the second wire and the original wire. By reference to resistance, state and explain whether the power dissipated by the second wire is more than, less than or the same as the power dissipated by the original wire.

..............................................................................................................................

.............................................................................................................................. [2]

(d) The circuit shown in Fig. 6.1 is modified by connecting a second battery, of e.m.f. 8.0V and negligible internal resistance, in parallel with the original battery and the original resistance wire, as shown in Fig. 6.2.

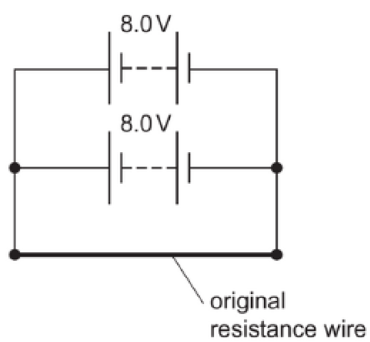



Fig. 6.2

By reference to the current in the resistance wire, state and explain whether the addition of the second battery causes the power in the original resistance wire to decrease, increase or stay the same.

6) b) A battery has electromotive force (e.m.f.) 4.0V and internal resistance 0.35Ω. The battery is connected to a uniform resistance wire XY and a fixed resistor of resistance R, as shown in Fig. 5.1.

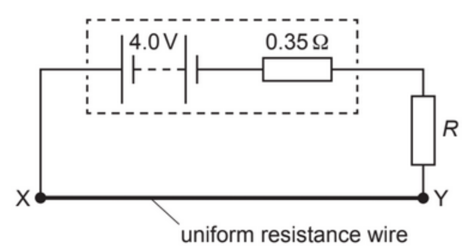



Fig. 5.1

Wire XY has resistance 0.90Ω. The potential difference across wire XY is 1.8V.
Calculate:
(i) the current in wire XY

(ii) the number of free electrons that pass a point in the battery in a time of 45s

(iii) resistance R.

(c) A cell of e.m.f. 1.2V is connected to the circuit in (b), as shown in Fig. 5.2.

The connection P is moved along the wire XY. The galvanometer reading is zero when distance XP is 0.30m.

(i) Calculate the total length L of wire XY.

ii) The fixed resistor is replaced by a different fixed resistor of resistance greater than R.
State and explain the change, if any, that must be made to the position of P on wire XY so that the galvanometer reading is zero

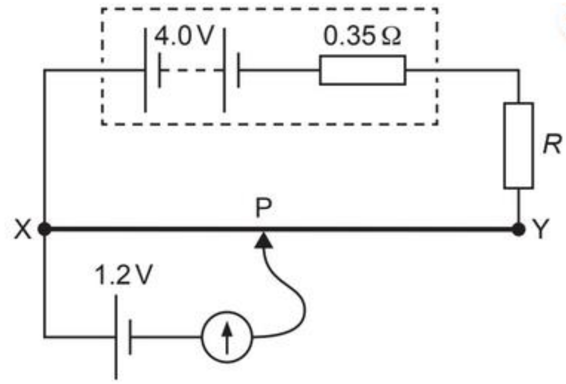


Fig. 5.2

7) a)A metal wire of length 1.4 m has a uniform cross-sectional area = $7.8 \times 10^{-7}$ $m^2$ . Calculate the resistance, R, of the wire. resistivity of the metal = $1.7 \times 10^{-8}$ Ωm

(b) The wire is now stretched to twice its original length by a process that keeps its volume constant. If the resistivity of the metal of the wire remains constant, show that the resistance increases to 4R.